ANALYSIS ON THE COUPLING OF BIOMASS GASIFICATION PROCESSES WITH A PARABOLIC TROUGH CONCENTRATING SOLAR PLANT

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ABSTRACT: The energy needed from gasification processes to convert a solid fuel, the biomass, into a gaseous one is usually supplied by the partial oxidation of the fuel in the gasification reactor. However, the use of solar power as an external thermal input is attractive to improve the energy content and the quality of the product gas. Solar parabolic trough (PT) technology, using molten salt both as heat transfer fluid and thermal storage medium can provide an energy input to a gasification reactor in a stable and continuous way throughout the whole process. The gas produced by a reactor supplied by solar energy has a better quality in terms of Low Heat Value, "cold gas efficiency", "carbon efficiency" and tar content. Molten salt, acting as thermal fluid in the heat exchanger within the reactor (in the place of hot gas) increases reliability and avoids unsafe service interruptions for the facility. At the same time, the abovementioned Concentrating Solar Plant (CSP) plant can benefit from the syngas. In particular this latter may be profitable for covering the CSP nocturnal losses, decreasing the use of fossil fuel, allowing power production in cogeneration to be used as heat for salts heating up, in order to have a power generation extension. To sum up, this paper investigates the benefits ensured by this coupling to both plant technologies and explains the method to be used in case of agro-industrial residuals used as feed.
Keywords: agricultural residue, biomass, gasification, syngas, concentrating solar power, thermal storage.

1 INTRODUCTION

Green energy is a very important issue for the present generation as well as for the future one and solar technology can greatly contribute to its spread all over the world. In addition, concentrated solar energy including thermal storage, can allow a proper coupling of different technologies such as gasification.

Gasification in fact, produces a gaseous fuel (syngas) from a solid one by a thermal degradation process.

The heat required for this process is generally supplied by the partial oxidation of the fuel particles in the gasification reactor through a gasification agent that in most cases is the oxygen from the air, but can also be pure oxygen, steam or even CO_2 [1]. Thus, if a renewable source like solar energy provides the energy to feed its endothermic reactions, the use of the energy included in the fuel for the conversion process is reduced as well as the related emission, in turn increasing its environmental sustainability.

In this paper, a gasifier fed by agricultural waste was analyzed in order to find an advantageous solution to feed a gasification process by a solar trough concentrating solar power (CSP) plant, using molten salts (a mixture of 40wt% in KNO_3 and 60% in $NaNO_3$).

CSP technology as heat source for gasification has been proposed many times over the last years, also by extensive modeling ([2]-[4]).

In this field Ravaghi-Ardebili et al. [5] analyzed a unified process consisting of a CSP plant, which supplies the produced steam to the biomass gasification process as well as to the downstream conversions to chemical commodities and energy carriers for methanol/dimethyl ether production at approximately 400 °C. Palumbo et al. [6], instead, tested an indirectly heated hybrid co-feed system at high temperatures, using also CSP technology, with biomass, methane, and steam as reactants. Syngas with enriched H_2 content and low CO_2 yield was shown to be achievable with varying dependence on biomass type, temperature, and reactant ratios.

Despite these latter cases, up until now it has often been proposed to feed the gasification process having the solar radiation directly concentrated on the reactor surface, or inside of it, via a glazed area, for which many experimental campaigns have been carried out ([7]-[12]) with this sole aim.

This kind of process, which can be defined as direct exchange uses the Central Receiver System (CRS) technology that allows very high temperatures (~1000 °C) to be reach. The reactor's absorbing surface can be made of materials having high selectivity or being transparent to the radiations providing power directly to the biomass inside the reactor. In this last case, the efficiency is higher even though the fouling on the glass can create problems [10]. Both cases, indeed, have a high temperature gap inside the reactor due to the localized heat source, which is not convenient for limiting heat losses [11]. This configuration however, in addition to some technical complications, generates a gasification process directly dependent on solar radiation and thus is unstable [12].

Daily gasification reactor start-up, in fact, shortens the plant lifetime. On the other hand, a daily thermal storage, particularly attractive with the solar parabolic trough technology but possible also for solar tower plants, allows an indirect cycle, where solar energy is collected by a thermal fluid. In this case, if the abovementioned molten salts are used, they can be both thermal storage media and thermal fluid, to supply the reactor when energy is required. Solar parabolic trough, is the most mature technology for concentrated solar plants, accounting for more than 90% of the currently installed CSP capacity [13]. In addition, Corona et al. [14], after a Life Cycle Assessment applied to solar parabolic trough plants hybridized with different fossil and renewable fuels, claimed that the characterized results suggest that the operation of the CSP plant, in solar-only mode, produced the lowest environmental impact in almost every category.

This CSP technology is based on parabolic mirrors that concentrate the sun's rays on heat receivers (e.g., steel tubes) placed on the focal line. Receivers have a special coating to maximize energy absorption and minimize infrared re-irradiation. Therefore, they work in an evacuated glass envelope to avoid convection heat losses.

The solar heat, as said, is removed by a heat transfer fluid (e.g., synthetic oil, molten salt) flowing in the receiver tube.

Mirrors and receivers track the sun's path along a single axis (usually East to West) [15].

In the most diffused way, thermal storage can be ensured by one or two tanks, filled with molten salts.

2 MATERIAL AND METHODS

In order to propose an advantageous way to couple a CSP provided of TES (Thermal Energy Storage) system, and in particular a solar parabolic trough plant with a gasification reactor, this work aims to:

- find the endothermic reactions of the pyrolysis/gasification process to be supplied by an external source, in particular solar energy using molten salts as heat transfer fluid (HTS) to carry out an energy assessment. It is worth to remember the constraint of 550 °C as maximum temperature;
- propose a suitable reactor able to meet all criteria abovementioned;
- assess a CSP plant in order to verify the size and the advantages of this kind of coupling.

Another main aspect, consisting of the analysis of the mechanisms to obtain a high quality syngas through extensive experimental analysis including an in depth analysis on the biomass gasification process was carried out. It was specifically devoted to agricultural waste, focusing largely on the reactor temperature and its performance and is described in the Liberatore et al. paper [16].

2.1 Energy assessment

The assessment of the energy required by the reactions is an important step for sure. For our objectives it needs to deepen mainly the endothermic reactions, namely the drying and the pyrolysis, because the heat supplied by the exothermic reactions occurring at high temperature have to be mainly provided by the abovementioned solar source.

Aim of this work is to find the reactions to be supplied at a temperature compatible to the molten salts in the solar troughs, the way to carry out this process, propose a proper reactor design and finally size the solar plant to be best coupled with the gasifier.

It is worth paying particular attention to the following aspects:

- low heating rate, because it influences the residence time of the biomass and its products. Values of about 10 K/min, typical of a slow pyrolysis, promote the exothermic char formation and the secondary reactions of the primary gaseous products.
- mass transport restriction to prevent a rapid escape of the primary pyrolysis gas from the reactor, to avoid the char formation and the promotion of secondary reactions of the primary gaseous products (tar in particular). In fact, these reactions with longer residence time can take place inside the char porous structure and are mostly exothermic (partial oxidation, re-polymerization, condensation and so on).

In these conditions, in order to set the drying and pyrolysis development at room pressure, the He et al. model [2] has been applied to a generic wooden biomass together with the following assumptions:

- 25-170 °C: the energy required accounts for the sensible heat to cover the temperature range and the latent heat for vaporization of the fuel moisture. In this assessment, a biomass with a moisture content of 15 wt% (on a wet basis) was considered, because it is in the characteristic range of the woodchips, used in the medium-size plants. In addition, it is obtainable through the natural drying of the solid fuel, consequently saving costs. The percentage related to the residual solid was hence referred to as dry biomass, namely 85% of the initial one. The temperature range mentioned above has been divided into two parts: the first (Q_{1a} by eq. 1) considering temperatures up to water evaporation, taking into account the wet biomass heating; the second (Q_{ev} by eq. 2) considering water evaporation, and the third part (Q_{1b} by eq. 3) which considers the dry biomass heating as well as the vapor.

$$Q_{la} = m_b \cdot c_{p,b} \cdot \Delta T_1 \quad (1)$$

$$Q_{ev} = m_{steam} \cdot \lambda_{evap} \quad (2)$$

$$Q_{1b} = m_b \cdot c_{p,b} \cdot \Delta T_3 + m_{steam} \cdot c_{p,steam} \cdot \Delta T_3 \quad (3)$$

Equation (4) from Jalan et al. [18] was used to compute the heat capacity of the considered biomass.

$$c_{p,b} = 1112 + 4.85 \cdot (T - 273) \quad (4)$$

- 170-260 °C: here, warm up of dry biomass and steam are the only processes taking place. The energy requirements has been assessed with the (eq. 3), taking into account the first degradation of the solid matrix (3.5 wt%). The calorimeter, indeed, detected that the humidity evaporation was totally happened below 170 °C. In these first two steps, the sensible heat to be provided is almost the same of the one reported by He [2]. Nevertheless, in this work the wet biomass needs more energy for its evaporation, 341 kJ/kg, that is not requested by the He analysis.
- 260-400 °C: in this range the complex degradation reactions must be considered, with the simultaneous and competitive development of char and biomass devolatilization reactions. Solid mass reduction increases to a total of 56.4 wt% (on wet basis).

Although it is possible to roughly estimate the heat capacity of char, it is very hard to assess the heat capacity of the gas, which depends on the high number of species and their concentration, changing continuously with temperature.

Thus, the energy balance was assessed by summing the experimentally measured heat (DH_{exp}) of the dry fuel pyrolysis reported by He et al. [2], and the sensible heat needed by the moisture evaporation (eq. 5).

$$Q_3 = \Delta H_{exp} + m_{steam} \cdot c_{p,steam} \cdot \Delta T_3 \quad (5)$$

- 400-600 °C: in this temperature range, a further char increase in temperature and a reduction of the solid fraction (about 8.7%) occurs, thus the biomass degradation is almost completed. The energy required (Q4) was computed as in the previous temperature range by the eq. 6.

$$Q_4 = \Delta H_{exp,4} + m_{steam} \cdot c_{p,steam} \cdot \Delta T_4 \quad (6)$$

Table I reports these results. The obtained value (1040 kJ/kg) is confirmed by other experimental studies [17] with comparable moisture content. In these works, all values measured by the differential calorimeter slightly exceed 1.0 MJ/kg.

Table I: energy demand of the pyrolysis (biomass with moisture content of 15%)

Step	**DT [°C]**	**Solid residue [%]**	**Energy demand [kJ/kg]**
1 (sensible part-liquid)	25-100	100	106
1 (latent part)	100	100	341
1 (sensible part-vapor)	100-170	85	120
2	170-260	82	188
3	260-400	34	152
4	400-500	31	67
5	500-600	27	66
Total	25-600	27	1040

2.2 Reactor Proposal

In order to effectively design the reactor, it is necessary to minimize the energy consumption at temperatures higher than 540 °C, because 550 °C is the limit of the molten salts operation, that is the thermal fluid and heat storage media for the solar plant under discussion. This can be achieved by separating the biomass at the bottom of the gasifier, from that at the top, where drying and pyrolysis take place. In this part, a molten salts heat exchanger, fed by the CSP, can be introduced in order to supply the endothermic reactions. Such a configuration, except for the use of an external source, is known as a "two-stage" reactor, because it takes shape from a first chamber for the drying and pyrolysis followed by another one where the pyrolysis products undergo oxidation and reduction thanks to gasification agents (e.g., air, oxygen, steam, etc.).

The heat exchanger can be assumed as consisting of circular plates, where molten salts flow in countercurrent, between the ceiling and the floor of each chamber in which biomass is handled and set down (figure 1).

In practice, the exchange area for each plate is equal to a disk with the following three elements missing: an internal circle for the tubes, in the center, where the molten salt goes up before entering its dedicated space between the biomass chambers; a circular sector to allow the biomass to enter its devoted room and another to leave it and going down.

The biomass handling is obtained by proper blades, which are arranged perpendicularly to the plates in a circular motion. Hence, the biomass rotates, driven by the blades over the plate surface, up to reach the empty circular space and fall into the plate below, where it finds the other biomass. It does not enter the space occupied by molten salts, because also this last room has the same shape with a correspondent empty circular sector.

By limiting the blades speed below 10 rpm, besides a good distribution of the biomass bed, it can also be prevented the fast gas escape and the deposition of solid particles in the walls, thus avoiding fouling problems during the operation.

A blower in the lower part of the reactor can extract the produced syngas. Before leaving the gasifier, the syngas travels through the porous matrix represented by the char where most of the cracking reactions occur; as a result, at the exit, the gas is at a lower temperature than the average temperature at the reduction zone.

The passage through the char, also allows the gas to transport ash and particulate; it is therefore necessary to have a cyclone filter. After, it can enter into an exchanger, which is assumed to have an inlet temperature of 700 °C and releases the heat to warm the air (gasifying agent) from a temperature of 25 to 670 °C.

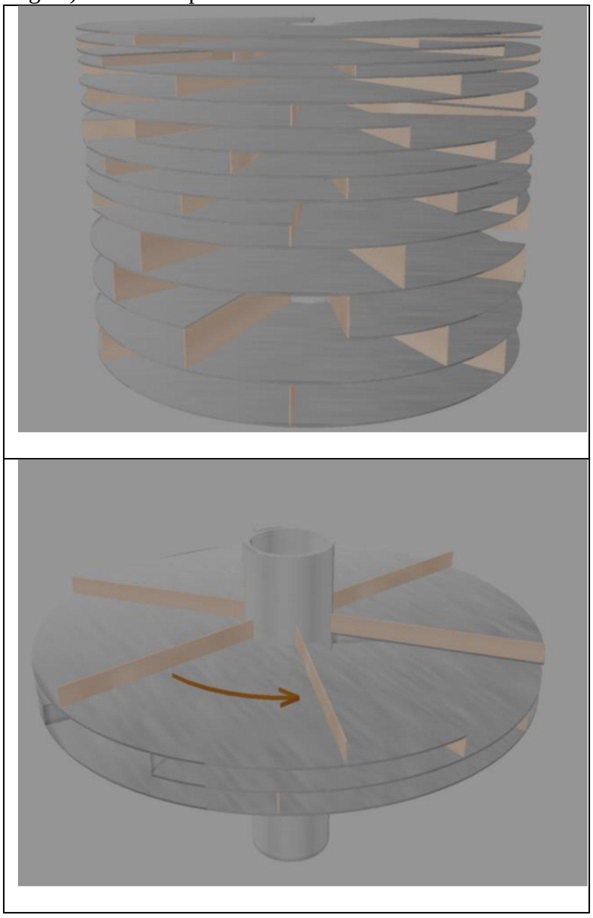

Figure 1: particular of the heat exchanger system and biomass handling inside the top part of the reactor.

2.3 CSP plant assessment and coupling with the reactor

In this study, in order to evaluate the sustainability of the proposed system, a coupling of a downdraft gasifier and a solar parabolic trough plant was considered. A gasification plant needs a continuous operation, because operative interruptions generate a large thermal stress in-turn reducing the life span of the equipment. Shut-down operations, in fact, involve excessive fouling of gasifier parts due to the high tar generation by pyrolysis, which become preeminent during cooling when tar thermal degradation, which is possible through the oxidation reactions, is absent. Alternatively, in order to preserve the gasifier, it would be possible to carry out complete biomass combustion inside the reactor, but this reduces the process efficiency for the relevant fuel demand, if performed daily. In this framework, it is clearly important arrange the solar plant with a thermal storage system as to ensure the continuous daily operation of the gasifier, namely a "storage time" of 16 hours, assuming 8 hours of daily direct irradiation. Through the energy assessments, previously described, the thermal power necessary to supply the gasifier can be calculated. It was assumed to design a downdraft gasifier able to yield 800 kW_{th}. This size can ensure temperature homogeneity and correct blending of air in the process where this is the only gasification agent.

With a gasification efficiency (η_g) of 0.8, which is usual for this kind of reactors and a Low Heating Value (LHV) of about 17 MJ/kg, which corresponds also to the one found in the experimental analysis, a biomass flow of about 215 kg/h is obtained. The energy required of the process up to a temperature of 500 °C, which corresponds to the drying and almost the whole pyrolysis is 974 kJ/kg. Thus, the residual power to be supplied is 58.15 kW_{th}. Accounting however, for 3% of losses, the solar plant must provide about 60 kW_{th}. A solar plant capable of ensuring this continuous power for the whole year was sized, it was assumed to be located in Italy (Priolo Gargallo-SR: 37.1N; 15.1E, Direct Normal Irradiance (DNI): 1936 $kWh/m^2/y$ corresponding to 5.3 $kWh/m^2/d$), it was used eq.7 to compute the mirror surface (A) with a global efficiency η_{gl} (average in the year) of 0.46 (assessed by the SW SAM®):

$$Q = A \cdot DNI \cdot \eta_{gl} \quad (7)$$

Hence, assuming 8000 working hours, the energy Q that the CSP plant has to provide is 60x8000 = 480,000 kWh/y, namely 60x24 = 1440 kWh/d. So, the theoretical mirror surface is 590.2 m^2, corresponding to just more than one collector for commercial PT. In order to ensure the continuity of the gasifier operation also during winter however, it is necessary to consider the November characteristic (Figure 2) values of DNI (3.06 $kWh/m^2/d$) and the corresponding η_{gl} (31%). In this month η_{gl} is lower than the one considered for the average in the year because of its reduced average DNI, which is correlated with the thermal collector efficiency and the cosine effect [18]. The month of November has been considered, because in Priolo Gargallo it is the month with the lowest DNI value over the annual operating period. In December, indeed, there is scheduled maintenance and hence, the plant is expected to remain non-operational. The resultant mirror surface has hence, a dimension of approximately 1518 m^2. As for the Thermal Energy storage, applying eq. 8, the volume of the storage tanks can be assessed through the molten salt mass (M_{ms}) calculation:

$$Q_s = M_{ms} \cdot \int c_p \cdot \mathrm{dT} \quad (8)$$

Since Qs, namely the energy to store, is equal to 60x16 = 960 kWh/d, the TES volume is 6 m^3 for each of the 2 tanks (one for the cold and one for the hot salt), devoted to the gasifier; this volume results, considering a 25% of oversizing.

Nevertheless, this configuration has two great downsides:

- the small scale for this type of technology entails high costs and technical complications in terms of efficiency as well as achieving the correct temperature;
- during the periods with the highest thermal irradiation, the plant wastes a large amount of energy, in particular if it is designed for periods with low values of irradiation.

At the other hand, the introduction of one or more gasifiers in a large CSP plant could overcome these problems and benefit the solar plant as well; thus, further analysis was carried out. For the same site in Italy, a CSP plant using PT and the same binary molten with a peak power production of 50 MW_e and 7.5 hours of TES was considered. Sau et al. [18] assessed for this kind of plant a total mirror surface of 423,168 m^2, 760 collectors (8 per loop) of 556.8 m^2, with two storage tanks including about 8500 tons of salts each. It is evident that the insertion of the abovementioned gasifier has a negligible impact on this kind of CSP. Hence, a single reactor, receiving continuous power of 60 kW_{th} from the solar plant, can provide 800 kW_{th} (in terms of LHV of its product gas) which, considering the continuous operation of the gasifier, allows a daily energy production of 19.2 MWh_{th}. Therefore, if four downdraft gasifiers producing 800 kW_{th} were installed in parallel, the necessary mirror surface devoted to the gasifiers would be only about 5.6‰ of the total area (yearly average) and at a maximum of 1.43% (in November).

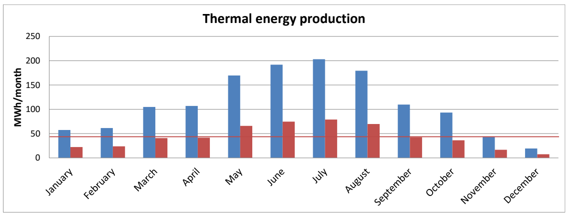

Figure 2: thermal energy production of a PT CSP plant in Priolo Gargallo (SR-Italy): in blue if the solar plant is designed for the November average DNI, in red for the year average one. The red line indicates the gasifier consumption in a month (43.2 MWh/month).

4 CONCLUSIONS

In this study the coupling of waste agricultural biomass gasification and solar parabolic trough technology was analyzed. A convenient configuration of the reactor allows to separate the endothermic steps, working at temperatures compatible with the molten salts (<550 °C) into the PT plant (drying and pyrolysis), from the others, which require higher temperatures, but are mostly exothermic. In this way, it is possible to supply the reactor by an external solar energy source and exploit the process continuity that a TES using molten salts can ensure. Molten salt, acting as thermal fluid in the heat exchanger within the reactor (in the place of hot gas) increases reliability and avoids unsafe service interruptions for the facility. At the same time, the CSP plant can benefit from the syngas. In particular it may be used for:

- covering the CSP nocturnal losses, decreasing the use of fossil fuel;
- allowing co-generative electricity production and its heat use for salts heating up, allowing power generation when the steam turbine does not make it;
- using the exhausted fumes for steam generation through the Heat Recovery Steam Generator (HRSG) technology in order to permit the continuous working operation of the steam turbine.

In conclusion, the gasification process and CSP technology coupling is technically feasible and beneficial for both technologies.

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